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SONIC-FLOW-ORIFICE TEMPERATURE PROBE FOR HIGH-GAS-TEMPERATURE MEASUREMENTS

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1 ## SUMMARY

A temperature-measuring device using sonic-flow orifices was developed and compared with existing temperature-measuring instruments. The device was compared with a standard shielded thermocouple in the temperature range from 710° to 1160° R and excellent agreement was obtained. In comparison with the sodium D-line reversal method, agreement to within 2 percent at conditions approaching thermal equilibrium was obtained in the temperature range from 3400° to 4000° R. A method of calibration was developed that eliminated the need for an absolute flow standard. Limitations and sources of errors of the device are discussed.

INTRODUCTION

The need for a device that can accurately measure local gas temperatures up to 4000° R has instigated much design and research. At present, platinum - platinum-rhodium thermocouples are being used with some degree of success up to 3400° R and preliminary experiments with iridium - iridium-rhodium thermocouples indicate a possible use at still higher temperatures. In both cases, serious radiation and wear problems confront the user, as well as the problem of reaction catalysis by a hot solid in the presence of combustibles. In addition, shifts in crystalline structure and a shift in calibration with use at high temperatures have been noted, particularly with the platinum junction.

Measurements of an average flame temperature by optical methods have been made with success by the sodium D-line reversal method and the two-color radiation method. Use of the D-line method to measure local gas temperatures in jet engines has been attempted with some success by coloring parts of the flame with sodium vapor and alining the optical path through this colored portion. Reference 1 reports the use of an interferometer for interpreting the cross-sectional temperature profile of a sodium-colored flame.

These optical methods must start with fairly expensive equipment that is tedious to calibrate and to operate and that becomes progressively more complex as refinements are made. Although excellent for many uses, the methods do not embody sufficiently practical usability for most jet-engine research.

A pneumatic device for measuring temperature, which employs subsonic flow across two orifices in series (reference 2), is commercially available. When the density and the pressure drops at the second orifice are known, the temperature of the gas entering the first orifice can then be determined from the measured pressure and pressure drop at the first orifice, providing the effective-area ratios of the two orifices are known. The device is insensible to error due to radiation and can be used over a very wide range of temperatures without modification. Inasmuch as the pressure drop across the two orifices is low, the device may be used in many cases without any need for a vacuum pump, and in no case would the vacuum requirement be an expensive one.

Because the sampling rate is flexible, the flow into the first orifice presumably may be adjusted to be proportional to the product of density and velocity ρV of the free stream, so that in a heterogeneous gas mixture a representative temperature sample is possible. Some disadvantages to this pneumatic device exist in that it is sometimes used under conditions where flow coefficients are not constant, so that calibrations would appear difficult. In addition, when the device is used in an exhaust stream of a jet engine, where pressure surges occur that are large compared with the pressure drop in the orifices, the data obtained are difficult to interpret.

The theory of a method that employs two sonic-flow orifices in series in order to measure, among other things, temperature is discussed in reference 3. References 4 and 5 describe methods for measuring an average duct temperature in a flowing gas by means of pressure-sensing devices. An investigation was conducted at the NACA Lewis laboratory to develop a sonic-flow device, capable of measuring high local gas temperatures in a gas stream, that is insensible to errors due to radiation and wear, is easily calibrated by some simple method, is inherently reliable in constancy of results, and is of simple construction. The device is described in detail. The development of this device was independent of the developments described in references 2 and 3.

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APPARATUS

Temperature-Measuring Device

The temperature-measuring device, shown in figure 1, consists of two orifices in series through which gases are drawn at sonic velocity, with provision made for measurement of pressure and temperature upstream of the second orifice. The small thin-walled orifice at the gas-sampling end (first orifice) was smoothly faired on the end of a water-cooled tube that covered the portion of the probe immersed in the hot gases. Downstream of the water-cooled portion the tube was enlarged and externally heated by an electric heating coil to prevent condensation, as well as to provide a uniform temperature profile so that one measured temperature is representative of the gas temperature entering the second orifice. The second thin-walled orifice was placed near the downstream end of the heated section and a pressure tap and thermocouple were positioned just upstream of the second orifice. For the probe investigated, the distance between the first and second orifices was $8\frac{1}{2}$ feet, 7 feet of which were electrically heated. The effect of the probe length was not investigated. The gases were drawn through the orifices by means of a vacuum pump. The pressure and the temperature were measured with an absolute manometer and iron-constantan thermocouple, respectively. Precision-bore orifices were not used and the method of calibration and use hereinafter described eliminates the need for more elaborate orifices.

Auxiliary Apparatus for Orifice Calibration

The only auxiliary apparatus necessary for calibration of the orifices was a positive-displacement meter and a vacuum pump. The method of use is discussed under the section Calibration of Orifices.

Auxiliary Apparatus for Probe Evaluation

Comparison with thermocouple in air. - The apparatus used for comparison with the sonic-flow temperature probe with a thermocouple in air over the lower portion of the temperature range consisted of a 5/8-inch-diameter duct, 60 diameters in length, in which the air could be electrically heated to approximately 1160° R. The temperature-measuring devices were inserted into the exhaust stream at the outlet of the duct.

Comparison with sodium D-line reversal method in propane-air combustion products. - Several burner configurations were used for the calibration of the probe in propane-air combustion products over the higher temperature range. The configuration discussed herein is shown in figure 2. The burner section consisted of a 1-inch-diameter brass tube cooled with a brass water-jacketed section. The flame holder was attached to a rod so that the tail-pipe length (distance between exhaust end of burner and flame holder) could be varied. 1303

In order to obtain a locally colored flame, a sodium-bicarbonate duster was incorporated that allowed a portion of the propane-air mixture to be blown over the sodium-bicarbonate dust and the resulting mixture to be carried through a tube to the desired delivery position. The flame-holder configuration used employed a perforated-plate flame holder rigidly attached to the sodium-bicarbonate delivery tube so that the delivery tube extended about 1/16 inch above the perforated plate.

The apparatus for the sodium D-line reversal method was standard and consisted of a calibrated tungsten-band lamp in series with a lens system and a spectroscope. Fuel-air - ratio distribution was determined with a NACA gas analyzer and gas velocities were determined with a micromanometer and a water-cooled pitot tube.

ANALYSIS

When a gas flows through a restriction and the pressure ratio across the restriction is such that sonic velocity is always maintained at the restricting area, the mass flow remains constant for any particular value of inlet pressure and density and is independent of the downstream pressure. In reference (6) it is shown that the critical mass-flow parameter for flow through an orifice can be expressed as a function of the upstream ratio of specific heats. Designating this function $f(\gamma)$, the critical-flow parameter can be expressed as:

$$\frac{PA}{W_c \sqrt{gRT}} = f(\gamma) = \frac{\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}}{\sqrt{\gamma}} \tag{1}$$

where

P total pressure ahead of orifice, (lb/sq ft)

A effective area of orifice, (sq ft)

W_c critical mass flow through orifice, (slugs/sec)

1303 g gravitational constant, (ft/sec^2)

R gas constant

T total temperature of gas in stream tube entering orifice, (°R)

$f(\gamma)$ function involving ratio of specific heats

γ ratio of specific heats

When two orifices are considered in series such that sonic velocity is maintained through each simultaneously and conditions upstream of the first and second orifice are denoted by subscripts 1 and 2, respectively, then

$$W_{c,1} = W_{c,2} \tag{2}$$

therefore

$$\frac{P_1\, A_1}{f(\gamma_1)\sqrt{gR_1T_1}} = \frac{P_2\, A_2}{f(\gamma_2)\sqrt{gR_2T_2}} \tag{3}$$

By assuming negligible change in R,

$$T_1 = \left[\frac{P_1A_1}{P_2A_2}\,\frac{f(\gamma_2)}{f(\gamma_1)}\right]^2 T_2 \tag{4}$$

When the static temperature of a gas having appreciable vibrational components of specific heat goes through a rapid change, as in the expansion to sonic velocity through an orifice, the vibrational energy in the gas lags the translational and rotational energy. In order to determine the effect of this lag on sonic flow through an orifice, the following theoretical model was investigated: In order to obtain the velocity distribution along the central streamline, incompressible sink flow to sonic velocity into an orifice at the end of a source-shaped tube was assumed. The dimension of the source-shaped tube approximated those of the probe used in the experiments. From this velocity distribution, using compressible-flow relations, the static translation-temperature distribution in distance and time was computed. The temperature-time relation between translational and vibrational temperature was approximated by $\frac{dT_{vib}}{dt} = \frac{1}{\tau}(T_{vib} - T_{trans})$, where τ is the molecular relaxation time of the gas and was taken herein to be 10^{-5} second and $\frac{dT_{vib}}{dt}$ is the rate of change of the vibrational temperature with respect to time. The curve of translational temperature plotted against time was then broken into steps and these steps integrated. As the translational temperature changed 17 percent, the vibrational temperature changed less than 1 percent, from which it is deduced that the gas acts as though it has no vibrational degrees of freedom; therefore, for all temperatures a nonvibrational value of γ (such as $\gamma = 1.4$ for air) is used. Hence the term $f(\gamma_2)/f(\gamma_1)$ in equation (4) goes to unity and T_1 is now determined by

$$T_1 = \left(\frac{P_1 A_1}{P_2 A_2}\right)^2 T_2 \tag{5}$$

The temperature T_1, as obtained from equation (5), is an average total temperature of the gas in the stream tube swallowed by the first orifice. The free-stream area of this stream tube may be approximated by the following equation:

$$\begin{aligned} A_0 &= A_1 \frac{\left(1 + \frac{\gamma-1}{2} M_0^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}{f(\gamma)\sqrt{\gamma}\, M_0} \\ &= \frac{A_1}{M_0}\left(\frac{1 + \frac{\gamma-1}{2} M_0^2}{\frac{\gamma+1}{2}}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \end{aligned} \tag{6}$$

where

A_0 area of free stream sampled

M_0 free-stream Mach number

A plot of A_0/A_1 against M_0 is shown in figure 3 for $\gamma = 1.4$.

When the water-cooled probe is immersed in hot gases, the film of gas near the outside walls of the probe will be cooled. Some of this cool film will be sucked into the first orifice, thus yielding an erroneous value of temperature unless sufficient flow is maintained along this outside wall to prevent this occurrence. The minimum free-stream Mach number at which the probe may be used can be approximated by setting A_0 in equation 6 equal to the frontal area of the probe and solving for M_0. At Mach numbers less than this minimum, an error would be introduced by the hot gases scrubbing the cold walls of the probe in reverse flow before entering A_1.

CALIBRATION

Calibration of Orifices

Flow characteristics for the orifices under sonic-flow conditions were obtained during the initial stages of the investigation with a positive-displacement meter. Air at room conditions was drawn through the wet-test meter, a calming chamber, the orifice to be investigated, a pressure regulator, and a vacuum pump. In all cases, the pressure ratio across the orifice exceeded that required for sonic velocity. Total pressure was measured at the calming chamber. Inasmuch as the pressure and the temperature upstream of the orifice were kept constant and the pressure ratio was varied by changing the downstream pressures, no flow correction to the meter was necessary. Runs were of short duration so that water-level changes due to incomplete saturation of air into the wet-test meter were not encountered. The different orifices were investigated and the preliminary calibration results are shown in figure 4. The ratios of the orifice diameters to the diameter of the tube were 0.115, 0.174, and 0.29. The data indicate that flow coefficients of thin-walled, sharp-edged orifices may be assumed constant at ratios of upstream total pressure to downstream static pressure in excess of 3.2. Such pressure ratios are therefore maintained for all work reported herein.

Selection of orifice-area ratios A_1/A_2, where subscripts 1 and 2 denote the first and second orifice, respectively, is determined by several factors: the temperature range to be examined, the pressure in the test section, and the vacuum-pump capacity. Inasmuch as it is desired to maintain a ratio of upstream total to downstream static pressure in excess of 3.2, the ratios of A_1/A_2 must be chosen to insure that this ratio is possible at all anticipated operating conditions.

From $\dfrac{T_1}{T_2} = \left(\dfrac{P_1 A_1}{P_2 A_2}\right)^2$, it can be seen that with A_1/A_2, T_2, and P_1 fixed, P_2 decreases as T_1 increases.

In order to insure the existence of the required pressure ratio over the range of operation, it can therefore be seen that if we choose $T_1/T_2 = 1$ and $A_1/A_2 \leqq 1/3.2$ so that $P_1/P_2 \geqq 3.2$, then for $T_1/T_2 > 1$, $P_1/P_2 > 3.2$ and the necessary condition is satisfied. The simplest method of selecting A_1/A_2 is to chose $A_1/A_2 \approx 1/3.2$. Then, when a vacuum is applied to the orifices in series at $T_1 = T_2$ by drawing room-temperature air through the two orifices, the effective ratios of A_1/A_2 may be found by measuring P_1/P_2, because $A_1/A_2 = P_2/P_1$ when $T_1/T_2 = 1$. If it appears, however, that at the highest expected value of T_1, P_2 would be low enough for the value of the pressure ratio across the second orifice to be less than 3.2, due to vacuum-systems limitations, another value of A_1/A_2 must be selected.

This value of A_1/A_2 would be such that the necessary pressure ratios across both orifices could be maintained at the maximum T_1/T_2, but would mean that at a lower T_1/T_2, and certainly at $T_1/T_2 = 1$, the required ratio of 3.2 across the first orifice would not be maintained, so the method previously described for finding A_1/A_2 at $T_1/T_2 = 1$ could not be employed.

This difficulty is overcome by selecting a third orifice A_3 such that $A_3/A_1 > 3.2$ and $A_3/A_2 \geqq 3.2$. Then, by first placing orifices A_1 and A_3 in series, and then A_2 and A_3 in series, and calibrating the effective area ratios A_1/A_3 and A_2/A_3

as before, $\frac{A_1}{A_2} = \frac{A_1/A_3}{A_2/A_3}$. It is apparent from the preceding discussion that any desirable ratio of effective areas can be determined without the need of an absolute flow standard.

The vacuum-system limitations reduce the flexibility of the probe by somewhat limiting the temperature range at which it can be used successfully, and by making spot checks of A_1/A_2 a little more difficult to obtain. If sufficient care is used in making the orifices ducting, a small amount of pressure recovery between the two orifices may be realized, so that a pressure ratio P_1/P_2 of perhaps $\gtrapprox 2$ would insure constant flow coefficients. These improvements doubtless can and will be made by the individual user. The use of a nozzle in place of the first orifice was found to introduce cooling errors. Calibration of the orifice could be maintained constant for extended running times when care was taken not to let dirty condensate be drawn into the orifice from the outside walls of the probe between runs. Frequent calibration checks are, however, recommended.

Evaluation Calibration of Instrument

Comparison with thermocouple in heated-air stream. - For the lower portion of the temperature range, the probe was calibrated in an air stream. The temperature of the air stream was measured at the exhaust plane with the probe and with a single-shield aspirating-type iron-constantan thermocouple. Hot gases were drawn past the thermocouple junction at a rate that would yield the highest electromotive force from this junction. A velocity and temperature survey were made across the exhaust stream. The temperature was limited by the heater employed to 1160° R or less.

The effect of gas-stream velocity on the temperature indication was investigated by holding the temperature at 1090° R and reducing the velocity until cooling errors were introduced because of the gases scrubbing the water-cooled tube prior to entering the orifice.

Comparison with sodium D-line in propane-air combustion products.- For the higher temperature ranges, the probe method was compared with the sodium D-line reversal method. The plane of measurement for the temperature comparison was at the exhaust plane of the burner configuration shown in figure 2. A comparison was made with a locally sodium-colored flame. Temperature and velocity profiles at the burner outlet were investigated with a perforated plate as a flame holder and with variations in fuel-air ratio and tail-pipe length. The fuel-air - ratio distribution at the plane of measurement was recorded.

RESULTS AND DISCUSSION

Evaluation in Air

The temperatures obtained with the probe and the shielded thermocouple for a stream velocity of about 60 feet per second, a flat temperature profile across the exhaust stream, and an approximately parabolic pipe-velocity profile are shown in figure 5 for a temperature range from about 740° to 1160° R. The agreement in the measurements by the two instruments is excellent.

The effect of varying free-stream velocity on temperature, as indicated by the probe, is shown in figure 6 for a gas-stream total temperature of approximately 1090° R. The temperature read by the probe, divided by the temperature of the thermocouple, is plotted against the average free-stream velocity of the stream tube swallowed by the probe. At average free-stream velocities above 11 feet per second, the temperatures read by the probe and by the thermocouple are in excellent agreement. At velocities below 8 feet per second, the probe indicates an erroneously low temperature. At velocities below 11 feet per second, as indicated by the vertical line in figure 6, the diameter of the stream tube sampled by the probe exceeds the diameter of the probe, and the error in the probe readings at these low velocities would therefore be anticipated because of the heat transfer from the gases to the water-cooled walls of the probe prior to entry of the gases into the orifice.

Evaluation in Propane-Air Combustion Products

In the higher temperature range (above 2500° R), the problem of obtaining temperature calibration becomes more difficult because of the absence of suitable standards of comparison.

With the burner configuration shown in figure 2, it was found that for an inlet velocity of 36 feet per second an approximately flat temperature profile was achieved across the colored part of the flame at the plane of measurement at tail-pipe lengths of 2 to $4\frac{1}{2}$ inches. With a 5-inch tail-pipe length, slight falling off of the temperature occurred near the edges of the sodium-colored portion of the flame because this colored portion approached the tube walls with the long tail pipe.

A comparison of temperatures indicated by the probe and by the sodium D-line reversal method for tail-pipe lengths of 3, 4, and 5 inches over a range of fuel-air ratios of approximately 0.05 to 0.09 is shown in figure 7.

At a fuel-air ratio of 0.0605 and a tail-pipe length of 3 inches, the probe gave values 6 percent lower than the sodium D-line reversal method. The data show that, as the tail-pipe length increases, and hence as the combustion reaction approaches equilibrium (longer tail-pipe, optimum fuel-air ratio), the temperatures obtained with the probe approach more closely those obtained with the sodium D-line reversal method.

Because it is difficult to assign meaning to a quantity temperature when thermal equilibrium does not exist, the discrepancies between the two methods should not be surprising. In addition, the influence of the assumptions made and the particular apparatus used should not be ignored. Although complete coverage of the possible deviations from the assumptions would be difficult to make with any degree of accuracy using available information, an order of magnitude of two possible sources of error and their direction are noted.

(1) Water-gas reaction. It is generally accepted that in sampling hot gases the water-gas reaction freezes at an equilibrium temperature of approximately 3240° R. (See reference 1.) Inasmuch as the highest static temperature at the throat encountered in this investigation was 3330° R, which represents an equilibrium constant of 4 as opposed to 3.8 for 3240° R, the approximate error (on basis of water-gas equilibrium alone) incurred by ignoring the reaction would be less than 0.1 percent. The error is in the direction of higher temperature readings for the richer mixtures.

(2) Incomplete combustion. Incomplete combustion going to completion after passing the first orifice in the probe could cause an error (with the combustion efficiencies upstream of the first orifice indicated by the probe at a tail-pipe length of 3 in.) of from 0.4 percent at low fuel-air ratios to 0.6 percent at high fuel-air ratios; both errors cause the indicated temperature to be low. This shift would be caused primarily by a change in the gas constant, inasmuch as the error resulting from changes in the ratio of specific heats would be less than 0.1 percent.

These approximations indicate a possible deviation of the order of 1 percent, whereas the actual deviations are of the order of from 2 percent where equilibrium is approached (longer tail pipe, optimum fuel-air ratio) to 6 percent at nonequilibrium conditions, which indicate that the sodium D-line reversal method, as employed herein, may give an erroneously high indication of temperature when the reaction is still going on. One reason for the error could be that in turbulent flames the combustion proceeds in pockets in which the sodium vapor would absorb and emit and which are surrounded by unburned gases below the temperature at which the sodium vapor would absorb and emit (reference 1), so that, in effect, the temperature recorded by the sodium D-line reversal method is a kind of average temperature of the sodium active pockets only. The probe samples at higher velocities than free stream and hence would tend to sample more of the hotter components of a heterogeneous mixture. The prejudice, it appears, is less marked in the case of the probe than in the D-line method.

Evaluation in the range from 1200° to 3000° R was not carried out because a suitable test apparatus was not available. Limitations due to carbon formation, liquid fuel impingement, and pressure fluctuations also remain to be investigated.

SUMMARY OF RESULTS

A temperature-measuring device was investigated (using sonic-flow orifices) and compared with existing temperature-measuring devices over temperature ranges up to 4000° R.

A comparison of the temperatures determined by the probe and by a single-shielded iron-constantan thermocouple located in an air stream that was progressively varied in temperature from a temperature of 710° to 1160° R indicated excellent agreement.

The temperature probe and the sodium D-line reversal method in the temperature range from 3400° to 4000° R and with the particular apparatus used indicated a difference in temperature of less than 2 percent at conditions approaching equilibrium and 6 percent at non-equilibrium condition.

A method was developed that eliminated the need for an absolute flow standard in calibrating this sonic-flow temperature probe.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, December 15, 1949.

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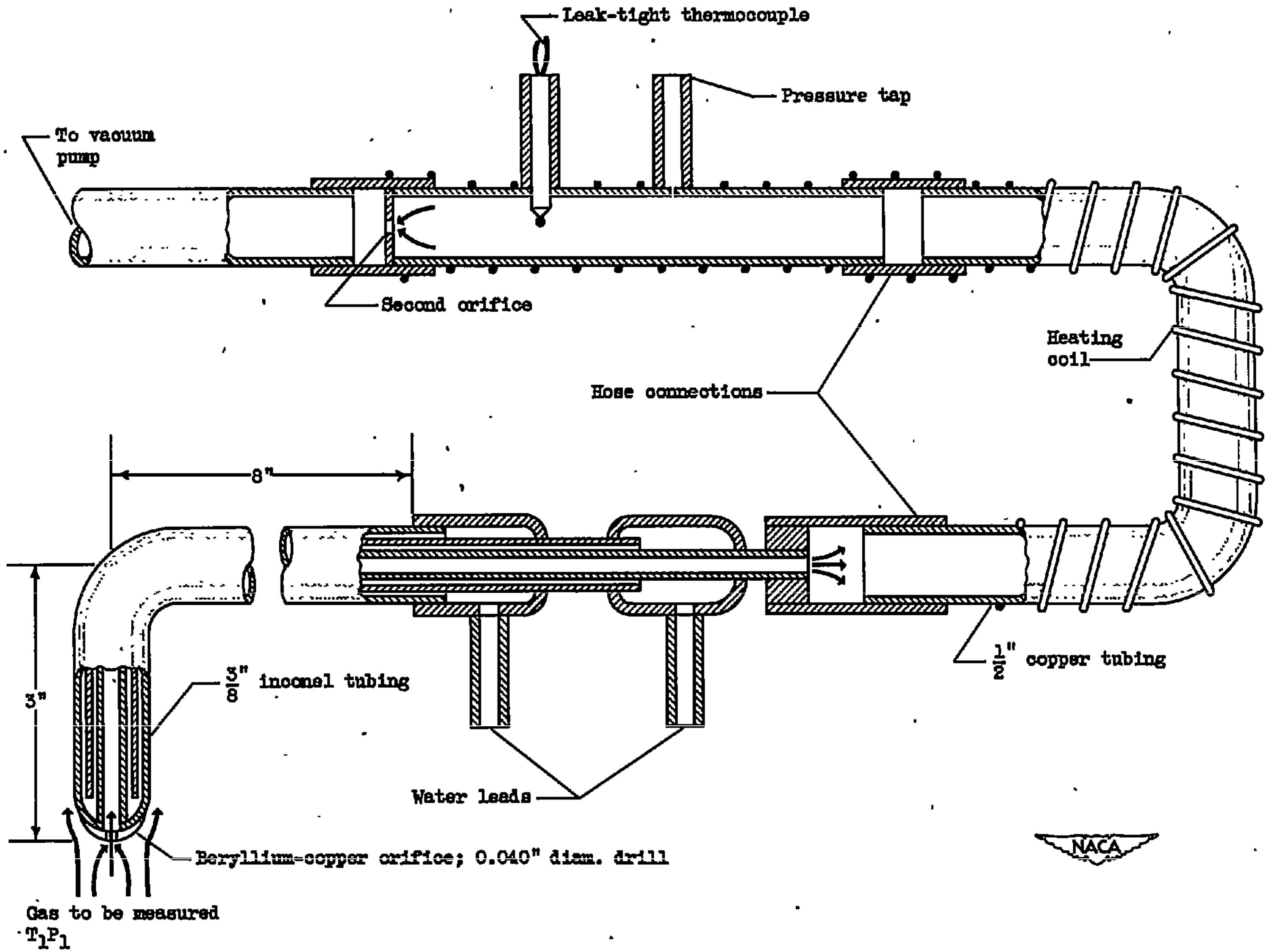

Figure 1. - Schematic diagram of sonic-flow temperature probe.

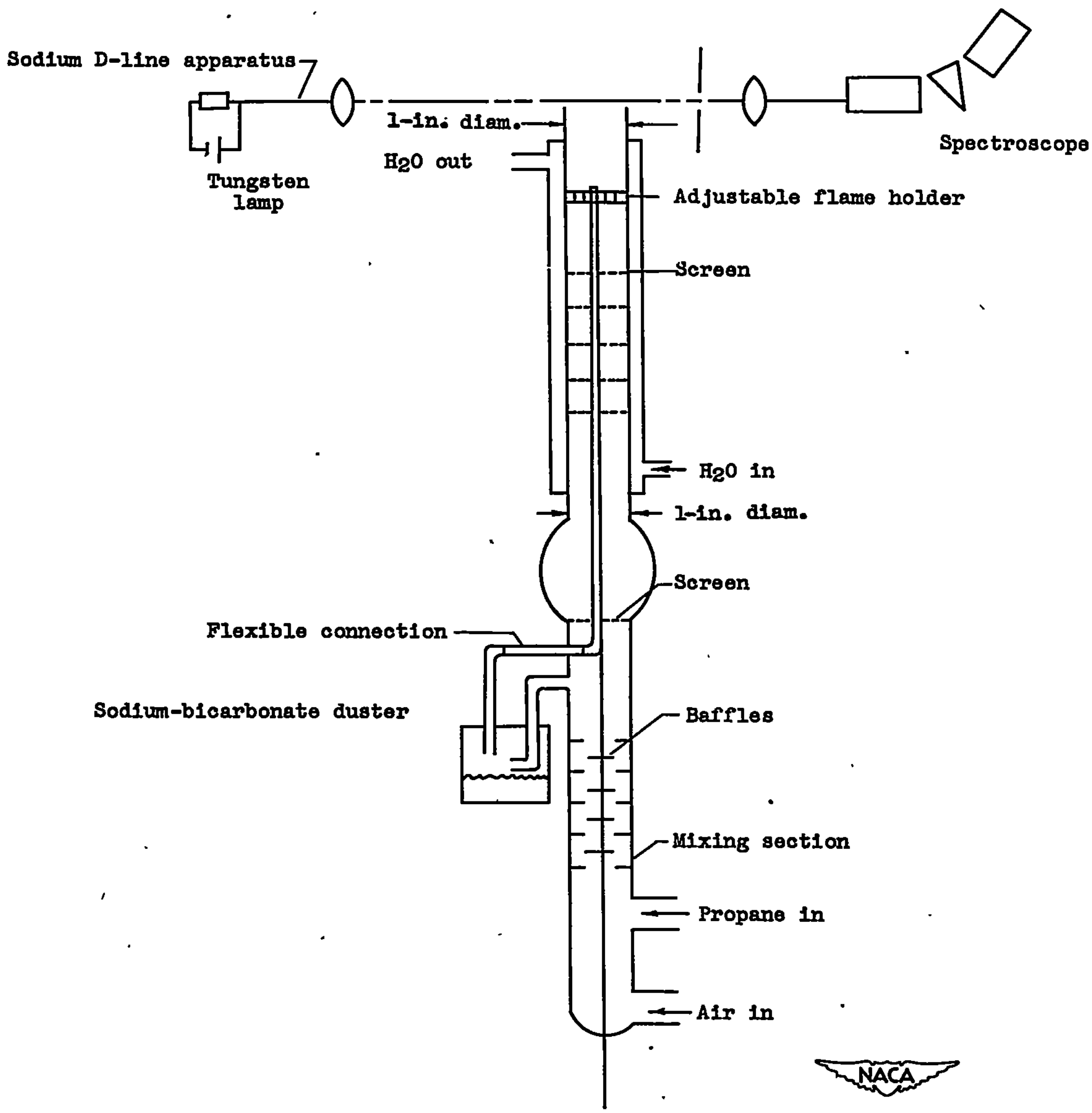

Figure 2. - Apparatus for calibration of high-temperature probe in propane-air combustion products.

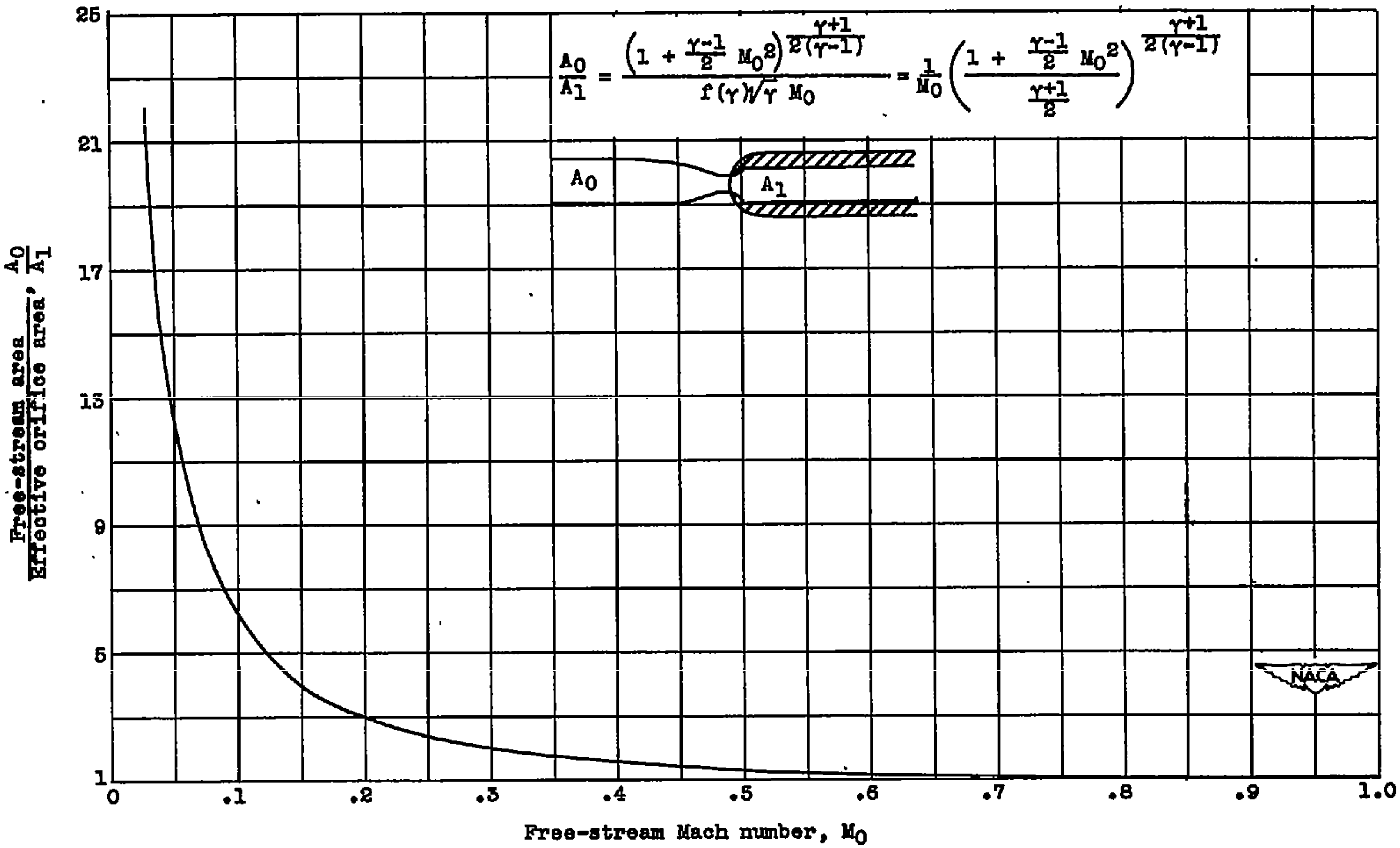

Figure 3. - Ratio of area of free stream sampled to area of first orifice as function of free-stream Mach number.

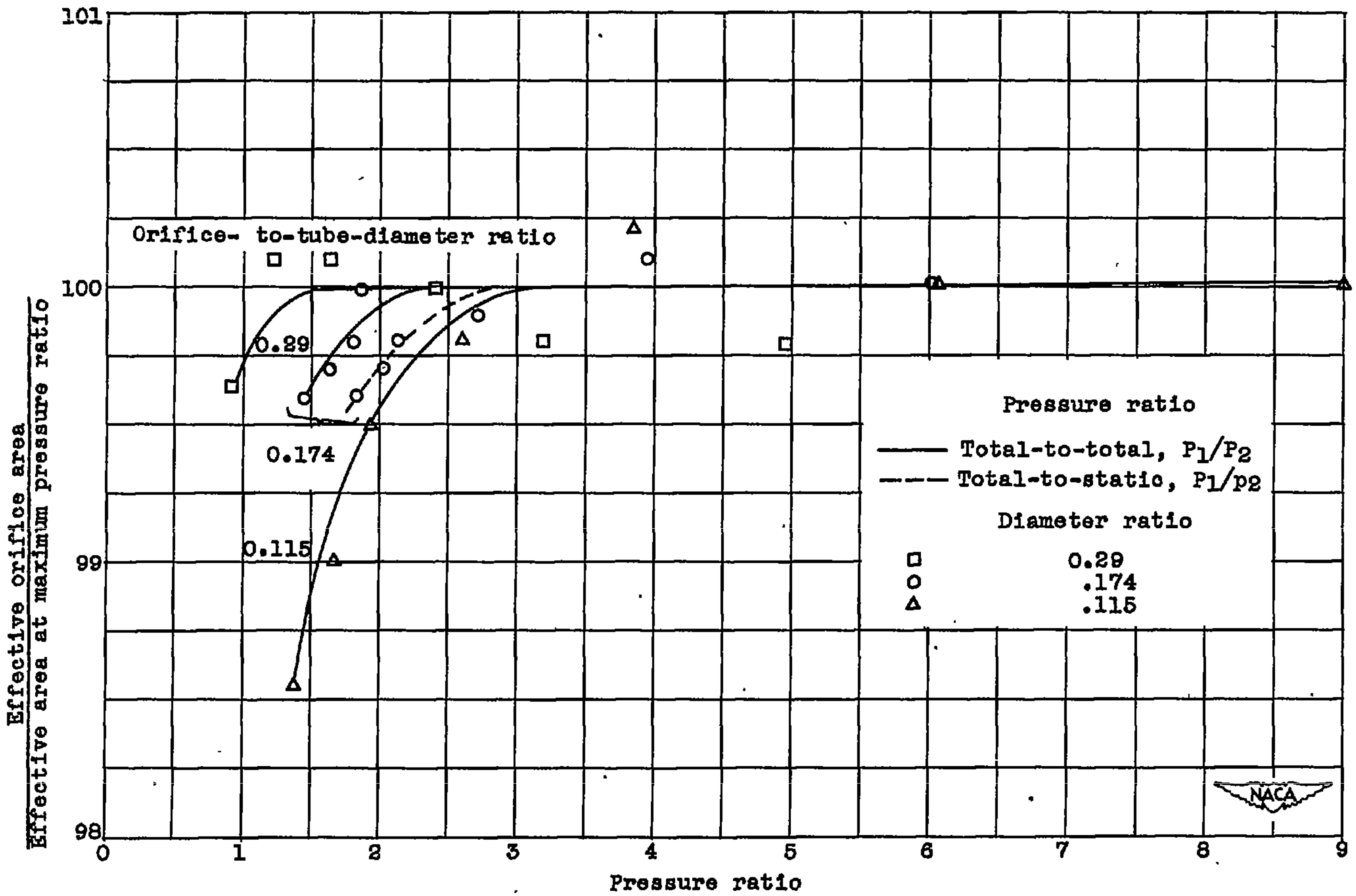

Figure 4. - Flow coefficients of thin orifices as function of pressure ratio across orifice.

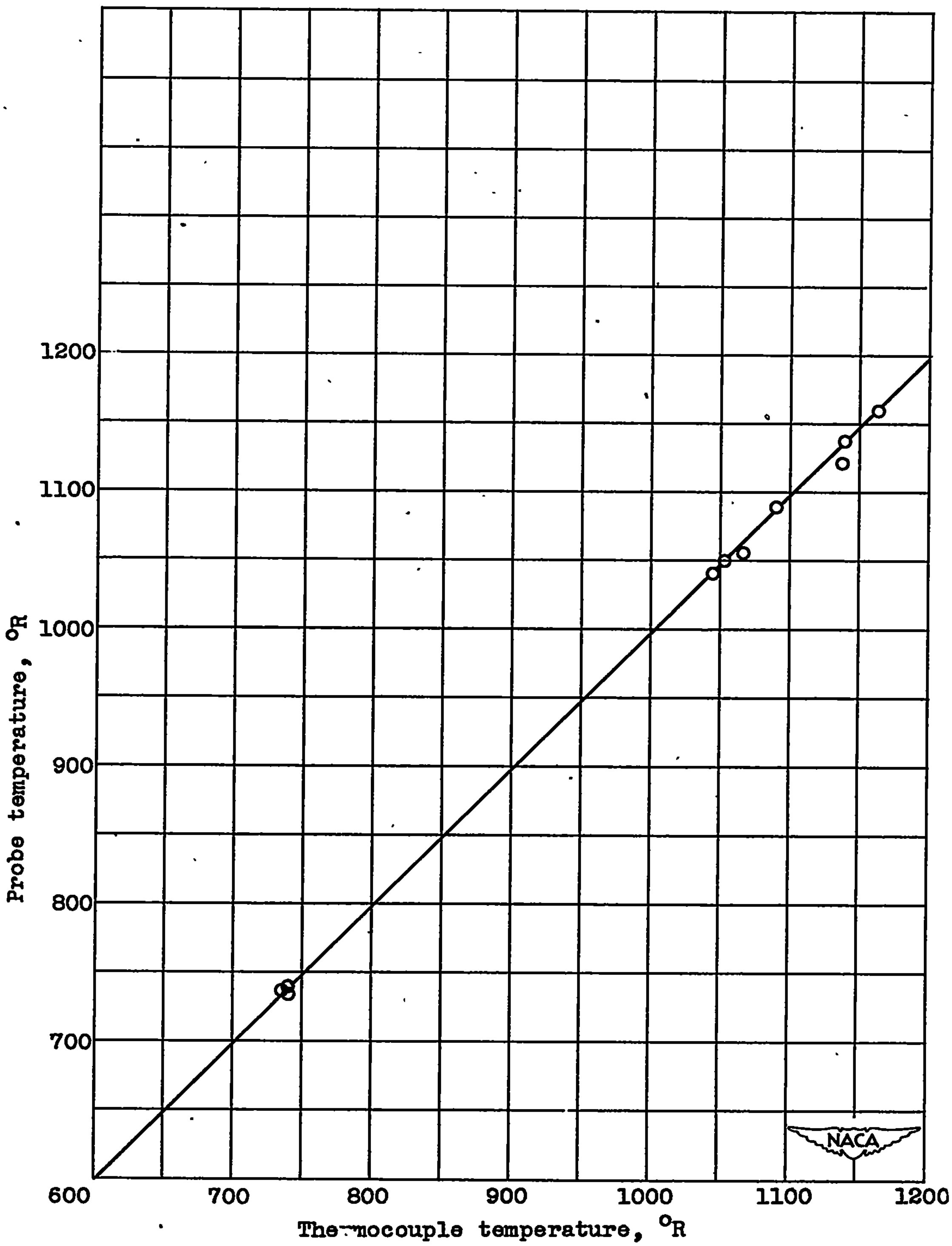

Figure 5. - Comparison of temperatures obtained by high-temperature probe with readings of aspirating shielded thermocouple in hot-air stream. Stream velocity, 60 feet per second; flat temperature profile; parabolic velocity profile.

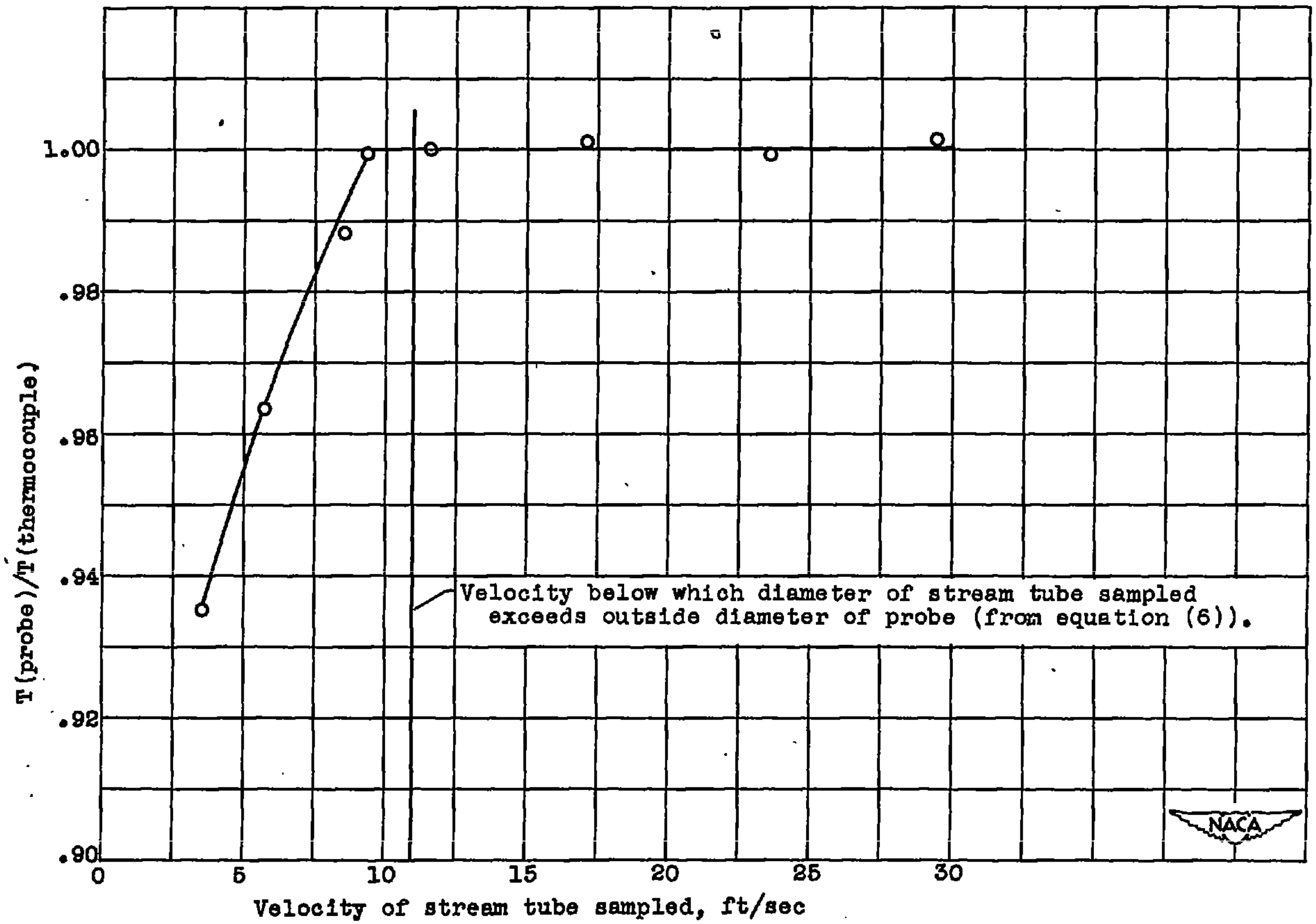

Figure 6. - Ratio of temperature measured by probe to thermocouple indicator as function of free-stream velocity or velocity of stream tube sampled at stream temperature, 1090° R.

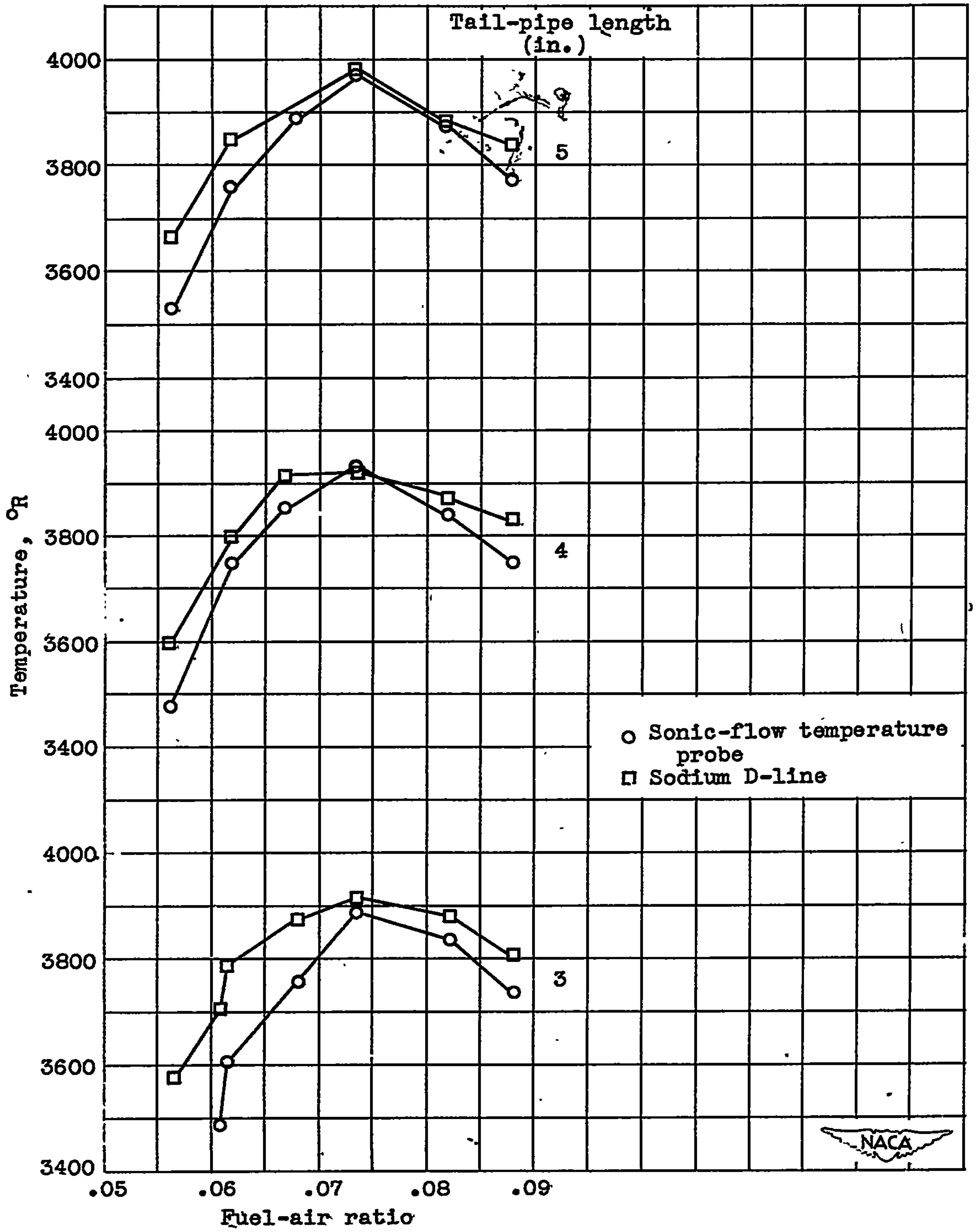

Figure 7. - Comparison of temperatures obtained with sonic-flow temperature probe and readings obtained with sodium D-line reversal method in apparatus shown in figure 3 with various fuel-air ratios.